TECHNICAL EVALUATION REPORT

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1.0 SUMMARY

The Specialists' Meeting on Advanced Rocket Performance Life and Disposal was held 23 to 26 September 2002. This was the second meeting on rocket motors organized by the Applied Vehicle Technology Panel since it was created in 1996. The aim of the meeting, described below, was achieved in that a snapshot of the state-of-the-art in areas covered by the meeting was accomplished. This evaluation report catalogs results along topic areas defined in an earlier AVT meeting and provides recommendations for future meetings and RTA activities in the area of Rockets and Energetics.

2.0 INTRODUCTION

The aim of the meeting was to provide a forum in which the latest advances in rocket motor technology could be presented. New propellants were emphasized along with critical operational oriented disciplines such as service life assessment, end of life disposal and environmental impact assessment.

The meeting was organized to have a keynote address and 36 papers organized along the following session themes:

- New Propellant Formulations (14 papers)
- Disposal and Environmental Issues (3 papers)
- Insensitive Munitions (4 papers)
- Service Life Assessment (6 papers)
- Internal Ballistics (9 papers)

3.0 BACKGROUND

Past meeting on rockets and ramjets sponsored by the Applied Vehicle Technology (AVT) Panel of the NATO Research and Technology Organization (RTO) and the Propulsion and Energetic Panel (PEP) of the NATO Advisory Group for Aerospace Research and Development (AGARD) lay an important foundation for this Specialists' Meeting. Meetings held in past years are as follows:

- Hazard Studies for Solid Propellant Rocket Motors (Reference 1)
- Smokeless Propellants (Reference 2)
- Insensitive Munitions (Reference 3)
- Airbreathing Propulsion for Missiles and Projectiles (Reference 4)
- Environmental Aspects of Rocket and Gun Propulsion (Reference 5)
- Service Life of Solid Rocket Motors (Reference 6)
- Small Rocket Motors and Gas Generators (Reference 7)

These past meetings have provided NATO nations the opportunity to meet and review progress in rockets and ramjets across a spectrum of work ranging from fundamental research to the development of final products. It is important that past results are recognized and addressed in future AVT meetings. In particular, recommendations from these meetings should find their way into subsequent meetings so that progress is realized and recorded in the area of rockets and ramjets.

At the 1999 Symposium held in Corfu, Greece, the list of Propulsion System Property Areas presented in Table 1 was defined. At that meeting, it was recommended that these areas be reviewed periodically at future AVT Specialists' meetings. To provide continuity between the Corfu Symposium and this Specialists' Meeting, these topics are used to organize this evaluation report. It will be seen that some of these topics were not covered in the meeting.

Table 1 Propulsion System Property Areas for Rocket Motors

- Performance
- Hazards
- Service Life
- Signature
- Combustion Instability
- Environmental
- Controllability
- Cost

4.0 EVALUATION

4.1 General

The meeting was well organized and attended with about 50 people attending each session. Discussions were lively with an average of 4 questions asked per paper. Unfortunately, not all of the questions are published in these proceedings because some Discussion Forms were not turned in after the meeting.

In general, most authors provided a preprint copy of their paper prior to the meeting. Because of travel problems, the keynote speaker did not make it to the meeting. This was disappointing. However, Mr. Drew DeGeorge kindly expanded his talk (2)[1] to cover general aspect of rocket propulsion. Paper no. 7 was withdrawn and paper no.4 was replaced after the original paper was withdrawn.

Overall, the technical content of the papers was excellent; however, technical details were missing in some papers – mainly those dealing with energetic materials. This could be due to the proprietary nature of the subjects discussed or the open nature of the meeting.

Papers presented ranged from basic research to applied technology. Two excellent papers serve as examples.

Basic research: "Nano-scale Studies for Environmentally Benign Explosives and Propellants," A. L. Ramaswamy, et al (12). This paper discussed an interesting concept that would use nano-carbon tubes as an ingredient in solid propellants. The concept offers the possibility of tailoring the tubes to allow scientific tailoring of a solid propellant's mechanical and burning rate properties. Currently, methods are being explored for manufacturing and tailoring the nano-tubes.

Final Product: "Development of a Gas-generator Propellant for a Rescue System for Submarines based on the Energetic Binder GAP," P. Jacob (8). This paper describes the development of a

[1] Numbers in parentheses refer to paper numbers in the Specialists' Meeting

solid gas generator being used by both the German and Italian Navies in a submarine rescue system that replaces air pressure systems.

4.2 Performance - New Propellant Ingredients

Three sessions were devoted to new propellant ingredients. These papers can be divided into two areas: 1) reviews of major programs and 2) development of propellant families.

4.2.1 Reviews of Major Programs

The IHPRPT program, presented by DeGeorge (2), involves U.S. Department of Defense and NASA working with U.S. industry to improve U.S. rocket boost and orbit transfer, spacecraft and tactical propulsion systems. The program was started in 1996 and has set ambitious goals for the year 2010. This paper lacked technical detail and was difficult to assess because it stated percentage improvements without referencing the baseline for improvement. Perhaps the open nature of the meeting made it difficult for detailed technical data to be presented.

The European co-operative program presented by Longevialle (3) involves 12 industrial entities from 8 European nations, but is much narrower in scope than the IHPRPT program. The paper presented results from a five-year program that dealt with topics ranging from the characterization of raw materials to formulation of propellants and the manufacture of small motors for performance evaluation. The study considered GAP, PNMMO, and PGLYN binders and ADN, CL20, and HNF oxidizers. Although new families of propellants with the aforementioned ingredients were made available by this program, additional work will be necessary to optimize combustion, mechanical, and thermal stability properties before these propellants can be used in full-scale rocket motors.

The U.K. propellant program presented by Cumming (5) considered many of the ingredients reported in (3). This paper was of a general nature and provided few technical details. Again, the open nature of the meeting could have made this necessary.

4.2.2 Development of Propellant Families

Work continues on the development of solid propellant families using the aforementioned new high energy ingredients. In general, challenges being addressed are high burning rate exponents, high mix viscosity, low solids loadings (HNF), and improvement in thermal stability. In addition, high cost and the unavailability of some solid ingredients remains a problem.

Unneberg (6) reported results for smokeless (AA signature per STANAG-6016) Gap propellants that use HNF, HMX, or CL20. Propellants were tested in sub-scale motors for ballistic properties. Each propellant studied exhibited unacceptably high burning rate exponents suggesting that all of these oxidizers will have to have ballistic modifiers if they are going to be used in full-scale rocket motors.

The use of ADN in solid propellants will not be feasible until thermal stability problems are resolved for ADN. The paper by Bohn (9) reported that laboratory tests had provided improvement of ADN thermal stability using at least seven different additives. Although a mechanism for ADN decomposition was postulated, the identity of the additives was not disclosed.

HNF oxidized propellants were studied in the laboratory by van der Heijden (10) who reported that high burning rate exponents, thermal stability, and low solids loading due to the needlelike shape of the HNF crystal continue to remain as unresolved problems for HNF propellants. Because these shortcomings have been known for some time, the practical application of HNF as the sole oxidizer in a solid propellant must be judged doubtful.

Menke (13) studied Minimum smoke (AB signature per STANAG-6016) propellants containing AP/CL20/GAP in the laboratory. Propellants studied had high burning rates with acceptable burning rate exponents and were considered candidates for boosters or high performance end burners where low signature is of interest.

Chan (20) presented both laboratory and small-scale motor results for an AP/AN/HTCE propellant that showed acceptable burning rate, card-gap, and cook-off characteristics. The primary motivation for this work was to demonstrate the feasibility of using the lower cost HTCE polymer over the higher cost HTPE polymer. Motor pressures up to 3000 psi were achieved to maximize specific impulse.

D'Andrea (37) presented a somewhat tutorial paper on the subject of burning rate tailoring for composite solid propellants. The main thesis of the paper was control of burning rate. D'Andrea stated that models to predict burning rate trends were inadequate. In his search for ways of controlling burning rate, he proposed various mechanisms that might control burning rate as a function of pressure. Despite these efforts, he concluded that burning rate tailoring in industry must still be accomplished by empirical approaches.

In general, it would seem that some of the propellant families are ready for scale-up to full-scale motor testing. However, the pace of progress will remain slow until effective ballistic additives are discovered and ingredients become available at acceptable costs.

A general comment about burning rate modelers is appropriate here. It seems to the evaluator that modelers of solid propellant combustion should direct their attention to the new ingredients and attempt to identify reactions that could be tailored to achieve desired burning rate characteristics. Data presented in the papers dealing with new propellant ingredients should provide a wealth of information for modelers.

4.3 Controllable

Lengelle (11) discussed design tradeoffs for a tactical missile powered by a hybrid rocket motor using hydrogen peroxide and hydroxyl ammonium nitrate for oxidizers and combinations of glycidyl azide polymer (GAP) and HTPB for fuels. This paper is an excellent example of applying basic science to design a rocket motor.

The gelled fuel papers by Weiser (14) and Ciezki (15) represent basic research being conducted in conjunction with a multi-year German program designed to investigate the feasibility of gelled propellants for tactical missile propulsion.

4.4 Insensitive Munitions

Desailly (19) described a phenomenological model designed to predict cook-off response for generic explosive-loaded munitions. The model, based on theory and empirical data from laboratory tests, should be coordinated with cook-off protocols originally developed under The

Technical Cooperation Program (TTCP), Panel W, ACTION Group 11 (WAG-11) and now maintained by the NATO Insensitive Munition Information Center (NIMIC).

Fisher (21) presented an excellent tutorial paper on existing and new solid propellant ingredients, propellant families and the use of these propellants in motors where IM is important. Fisher correctly points out that the solid propellant is an important element for achieving IM; however, other elements such as the stimulus for unplanned initiation and the environment in which the propellant is placed (viz, motor design and surrounding environment) are also important.

Tenden (22) described a full-scale motor demonstration program that showed the advantage of a composite motor case over a steel case for improving the IM capability of the Evolved Sea Sparrow Missile.

4.5 Disposal and Environmental Issues

Parker (16) described the development of a tool that would determine cost implications during the life cycle of a munition resulting from environmental impacts associated with materials in the munition. The heuristic model presented relies on expert opinion that is likely to be divided.

Stalker (18) discussed the difficulty of demilitarizing (Demil) munitions and the need for addressing Demil in the design stages of a munition. For the most part, Demil has not been addressed in the design stage of existing munitions. As a result, Stalker proposed that a database be constructed that would provide information to aid in Demil operations.

Herbst and Zatko (17) discussed the importance of re-cycling and re-using materials following Demil. The paper stated that a viable market exists for the use of Demil products in civil blasting applications

4.6 Service Life Assessment

Hyde's paper (23), dealing with the use of sensors for surveillance, addressed implementation of sensors into solid rocket motors and suggested that the solid rocket motor industry team with sensor developers. This teaming can be accomplished through joint efforts between Hyde and the AVT Task Group "MEMS Applications for Land, Sea, and Air Vehicles," chaired by Dr. Klaus Schadow.

Methods for predicting the service life of solid rocket motors were reported by Dodds (4), Biggs (24), Keizers (25), Neviere (26), Chevalier (27), and Huisveld (28). These papers address very complex processes associated with both mechanical and chemical properties of the motor constituents, the solid grain design, and the environment that the motor is subjected to during its life. It was disappointing to find that some of the authors were unaware of results from the aforementioned 1997 AVT sponsored Symposium titled "Service Life Prediction Symposium." One recommendation made by the Technical Evaluator for that symposium (Reference 6) was the development of a standardized method for predicting solid rocket motor service life.

4.7 Internal Ballistics

Tinaztepe (29) and Pekkan (30) presented results from programs that developed and validated grid generators and computational methods for predicting the flow field in solid rocket motors. The new code will eventually be coupled with a combustion instability model. The prediction of

flow fields coupled with both a burning model and a combustion instability model is an area where NATO standardization should be pursued.

Galfetti (31) and Cozzi (32) presented interesting ballistic properties associated with conventional AP/HTPB/AL solid propellants containing varying levels of different particle sized aluminum along with sodium nitrate for chlorine scavenging. For the ignitability of these propellants, it would be interesting if the author's would attempt to correlate the time to ignition for the different propellants with the burning rate associated with the pressure at which the ignitability test was conducted. Past studies have shown that the ignitability of markedly different solid propellants can be correlated by this burning rate. This suggests that ignitability is simply the time it takes to establish a stable thermal profile corresponding to the profile associated with steady state burning. For lower burning rate propellants, the thermal profile extends deeper into the propellant and thus requires a longer time to ignition.

Sorge (33), Fry (34), and DeLuca (35) described methods for measuring the burning rate of solid propellants. These papers contained material that should be considered for standardization. In particular, the work presented by Fry (34) was the result of an AGARD Working Group with 15 nations meeting over a 5-year period. Test approaches and methods of data interpretation endorsed by the Group should be extracted from the Working Group Report and promulgated as a NATO Standardization Agreements (STANAGs).

As a result of minor variations in the propellant composition throughout a solid rocket motor, prediction of full-scale rocket motor performance based on solid propellant burning rate characteristic measured from small-scale propellant mixes and strand burn rate tests can be different from measured motor performance. Ribereau (36) described a new model that incorporates burning rate variations due to particle segregation in the propellant during its casting in a motor.

4.8 Combustion Instability

No papers were presented on the subject of combustion instability. In recent years, work in this area has been reduced primarily because solid rocket motors have not experienced problems associated with combustion instability. This reduction is not the result of a final solution for combustion instability; rather, it is due to reduced defense budgets resulting in fewer new solid rocket motor development programs. As new solid propellant ingredients and new propellant families discussed in this meeting find their way into motor development programs, problems associated with combustion instability will be encountered. More specifically, when lower exhaust signatures are sought (e.g., Unneberg (6), van der Heijden (10), Menke (13), and Chan (20)), the lack of solid phase combustion products will result in lower acoustic dampening. In addition, when improved delivered performance is sought by increasing the motor chamber pressure (20), acoustic energy gains from the burning solid propellant will also increase. Finally, the influence of essentially all of the new ingredients on the acoustic admittance characteristics of a burning propellant is unknown but expected to be sensitive to high frequency pressure oscillations

In a recent U.S. Multi-Disciplinary University Research Initiative (MURI) Program directed at understanding combustion instability (Reference 8), Dr. Fred Culick, California Institute of Technology, has concluded that one of the greatest deficiencies in future studies of solid rocket combustion instability is understanding the acoustic admittance of the burning solid propellant. For future studies, new non-invasive measurement techniques are needed to properly characterize

the acoustic admittance of new higher energy solid propellants burning at pressures considered by rocket motor designers.

4.9 Cost

In light of reduced defense budgets, cost remains a significant driving factor in the development of new rocket motors. In this meeting, cost issues were not addressed explicitly; however, they were discussed in several contexts. For example, the IHPRPT program (2) stated that program goals must be met with no increase in cost to the propulsion system under consideration. This very ambitious goal can be contrasted with the more realistic approach presented during the discussion of Menke's paper on minimum smoke propellants (13). When asked about the impact of new costly ingredients in these propellants, the speaker responded that the propellant costs were small relative to overall weapon system costs. Moreover, a cost benefit analysis directed at personnel and system survivability would justify the added costs for more costly propellants.

4.10 NATO Interoperability and Standardization

The long-range strategy for the Research and Technology Organization (RTO) is given in Reference 9. Although the development of NATO standards and specifications is part of the RTO strategy, to date no NATO STANAGs have been promulgated based on result from RTO studies. AGARD, STANAG-6016 – Solid Propellant Smoke Classification (Reference 10). This STANAG was written based on results from a Working Group on "Terminology and Assessment Methods of Solid Rocket Exhaust Signature." This STANAG, promulgated in 1996, was referenced throughout the meeting.

It is suggested that the AVT Panel identify results from activities such as AGARDographs and Working Groups and convert these results to STANAGs.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The meeting was well attended, had good technical content, and created active technical discussions. But, areas for improvement are available.

The depth of the technical content was inadequate in some papers and a lack of continuity between results presented here with those from previous RTA meeting s was evident. Recommendations to improve future meeting are as follows:

- Number of Session Topics: The audience at a Specialists' meeting is comprised of specialists working in areas closely associated with the meeting's technical topics. As the number of technical topics covered in a meeting increases, the number of papers and authors the specialist can actively interact with drops proportionately. This meeting had too many topics. Perhaps only two or three of the topics presented in Table 1 should have been covered in a Specialists Meeting.

- Frequency of Meetings: One reason for having several technical topics in a single Specialists' meeting results from an inability to schedule meeting in a timely manner. The AVT Panel covers a broad range of topics and sponsors a limited number of meeting every year. As a result, a competition for meetings arises between representatives from these topic areas. With the trade-off between number of meetings and number of topics within a meeting, it is recommended that rocket propulsion seek additional meeting to lower the number of topics within a meeting.

• Session Classification: Classified sessions should be considered to allow more technical details to be presented and discussed during the meeting.

• Tutorial Papers: To improve continuity between current and past meetings, invited tutorial papers should be introduced at the beginning of sessions. The tutorial paper would set the tone of the session and summarize past RTA work in the session's technical area.

• Panel Discussions: The addition of a Panel Discussion at the end of a Topic Session the Specialists' Meeting would provide an opportunity to have a group of authors or independent experts to discuss progress achieved since the last meeting and suggest future needs.

• Discussion Form: About 60% of the Discussion Forms distributed to audience members who commented on papers were collected after the meeting. This low rate of return could have resulted because the Discusser deciding to not have the comment printed or the process for completed and collecting the Forms was inadequate. It is recommended that the existing process be reviewed and optimized.

• In general, many of the papers did not reference earlier relevant work completed by other authors. This shortcoming could be improved by RTA guidance that would request that authors be sure to provide references to earlier work.

Recommendations that address the technical content of the meeting are as follows:

• Combustion instability: When new ingredients as described in this meeting are used in full-scale rocket motors, combustion instability will be a problem. Although the meeting was very comprehensive in that it covered many of the topics in Table 1, the area of combustion instability was absent and should be the subject of a Specialists' Meeting in the near future. Results from the recently completed MURI program on combustion instability (Reference 10) could serve as a stimulus for such a meeting.

• Service Life Prediction: The authors of papers dealing with rocket motor service life prediction (24 through 27) should review results from the AVT Symposium on Service Life Prediction and request Working Group or Task Force status to develop a standardized method for predicting service life.

Apart from the technical details of the Specialists' Meeting, there are some aspects of the meeting that reflect on the AVT Panel and how it operates. The following recommendations are offered:

• Rockets and Energetics: The area of Rockets and Energetics appears to be becoming lost in the larger AVT Panel organization: The AVT Panel should consider creating a sub-panel on Rockets and Energetics to allow periodic review of the System Property Areas listed in Table 1. Competition with other areas covered under the AVT Panel appears to be making timely meetings difficult for the Rocket and Energetics representatives.

• Standardization: The AVT Panel should be examining Panel results with an eye on writing STANAGS. Paper no. 34, "Evaluation of Methods for Solid Propellant Burning Rate Measurement" (Fry, et al) has some concepts that could be standardized. It is

– recommended that the AVT Panel identify topics for standardization, convert these results to a STANAG format, and introduce them into the NATO process for ratification and promulgation.

6.0 AKNOWLEDGEMENT

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7.0 REFERENCES

1. “Hazard Studies for Solid Propellant Rocket Motors,” AGARD-CP-367, May 1984.
2. ”Smokeless Propellants,” AGARD-CP-391, September 1985.
3. “Insensitive Munitions,” AGARD-CP-511, July 1992
4. “Airbreathing Propulsion for Missiles and Projectiles,” AGARD-CP-~~511,~~ 526 September 1992.
5. “Environmental Aspects of Rocket and Gun Propulsion,” AGARD-CP-559, September 1994.
6. “Service Life of Solid Rocket Motors,” AGARD-CP-586, 1997
7. “Small Rocket Motors and Gas Generators for Land, Sea, and Air Launched Weapon Systems,” RTO-MP-23, AC/323(AVT)TP/11, April 2000.
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9. “A Research and Technology Strategy for NATO,” RTO-RTS-2000(S), AC/323(RTO)N/12(S), December 1999.
10. STANAG 6016 (Edition 1) – Solid Propellant Smoke Classification, DS/PCS/A(94)103 dated 19 July 1994.

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14. ABSTRACT
The Specialists' Meeting on Advanced Rocket Performance Life and Disposal was held 23-26 September 2002. This was the second meeting on rocket motors organized by the Applied Vehicle Technology (AVT) Panel since it was created in 1996. The aim of the meeting, described above, was achieved in that a snapshot of the state-of-the-art in areas covered by the meeting was accomplished. This evaluation report catalogs results along topic areas defined in an earlier AVT meeting and provides recommendations for future meetings and RTA activities in the area of Rockets and Energetics. The aim of the meeting was to provide a forum in which the latest advances in rocket motor technology could be presented. New propellants were emphasized along with critical operational oriented disciplines such as service life assessment, end of life disposal and environmental impact assessment.

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